Signals of composite electroweak-neutral Dark Matter: LHC/Direct Detection interplay

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Abstract

In a strong-coupling picture of ElectroWeak Symmetry Breaking, a composite electroweak-neutral state in the TeV mass range, carrying a global (quasi-)conserved charge, makes a plausible Dark Matter (DM) candidate, with the ongoing direct DM searches being precisely sensitive to the expected signals. To exploit the crucial interplay between direct DM searches and the LHC, we consider a composite iso-singlet vector V, mixed with the hypercharge gauge field, as the essential mediator of the interaction between the DM particle and the nucleus. Based on a suitable effective chiral Lagrangian, we give the expected properties and production rates of V, showing its possible discovery at the maximal LHC energy with about 100 fb^{-1} of integrated luminosity.

1   Introduction and general properties

The possibility that Dark Matter (DM) be related, directly or indirectly, to the physics of Elec-
troWeak Symmetry Breaking (EWSB) deserves the highest consideration. Indeed this has been
and is being extensively discussed both in weak-coupling and in strong-coupling scenarios of
EWSB. The strong-coupling case is of interest to this paper, without specific reference to any
detailed model[1].

We consider the case where the forces responsible for EWSB respect a global (quasi-)conserved
charge X which enforces the (quasi-)stability of the lightest particle, Φ, with non vanishing X.
Φ is a candidate DM particle. Its mass, m_Φ, is in the TeV range, characteristic of the strong
forces that may give rise to EWSB. This particle is made of constituents that feel the strong force
and carry non-vanishing electroweak quantum numbers, but is itself electroweak-neutral. This is
needed in order to suppress the tree-level coupling of Φ to the Z-boson, which would be in conflict
with direct DM searches.

At face value, the cosmological relic abundance of the Φ-particles is too low to explain the
observed DM energy density, Ω_{DM}, normalized as usual to the critical cosmological density. We
have in mind the effect of two body processes, $\Phi\bar{\Phi} \leftrightarrow Q\bar{Q}$, where Q is any unstable particle
lighter than Φ, also feeling the new strong force. For example, longitudinal W and Z bosons may
play the role of Q. The associated thermally averaged cross section is far bigger than the needed
$\langle\sigma v\rangle \approx 1\text{pb}$, since

$$\langle\sigma v\rangle \approx \frac{\lambda^4}{4\pi m_\Phi^2} f\left(\frac{m_\Phi^2}{\Lambda^2}\right) \approx 10^6 \,\text{pb} \left(\frac{\lambda}{4\pi}\right)^4 \left(\frac{\text{TeV}}{m_\Phi}\right)^2 f\left(\frac{m_\Phi^2}{\Lambda^2}\right), \tag{1.1}$$

where $\lambda \approx 4\pi$ is a Naive Dimensional Analysis (NDA) estimate of the strong coupling λ, and the
model-dependent function f of the ratio between the Φ-mass and the scale Λ characteristic of the
new strong interaction is of order unity for $m_\Phi \approx \Lambda$.[2]

We are thus led to consider the case where the relic abundance of Φ-particles originates from a
$X - \bar{X}$ asymmetry, analogous to the standard $B - \bar{B}$ asymmetry responsible for the dominance of
matter over anti-matter in the present universe. An interesting aspect of this hypothesis is that one
can try to relate $\Omega_X = \Omega_{DM}$ to the standard Ω_B by assuming that X, like B or L, are all broken

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[1]For a review of microscopic models of strong EWSB see [1].

[2]In Ref. [2], strongly interacting DM belonging to a non-EWSB hidden sector was considered, with a thermal
freezout as the source of DM abundance. However, much higher DM masses up to 100 TeV were considered and
smaller than NDA couplings were assumed.

by mixed electroweak anomalies. In this case, non-perturbative electroweak sphaleron interactions at a critical temperature $T^* \approx 100 \div 200$ GeV may redistribute any original asymmetry, leading in particular today to [3]

$$\frac{\Omega_{DM}}{\Omega_B} = \mathcal{O}(10^2)x^{5/2}e^{-x}, \quad x = \frac{m_\Phi}{T^*}, \tag{1.2}$$

which can be about right, $\Omega_{DM}/\Omega_B \approx 5$, for m_Φ in the TeV range.

In this as in other cases of putative DM particles, the problem is to find experimental signals that would not only establish their existence but would allow a clear interpretation of their nature. To this end it is difficult to overestimate the interplay between direct DM searches and LHC experiments, as we are going to discuss.

2 Summary of direct detection signals

In absence of a detailed model, the possible signal in direct detection searches can be discussed by means of effective operators that mediate the interaction between Φ and the u, d-quarks or the photon [4]. The Φ-particle can be either a complex scalar or a Dirac fermion.

If Φ is a scalar, the dominant interactions are described by

$$O_1 = \frac{1}{\Lambda^2}(\Phi^*\overleftrightarrow{\partial_\mu}\Phi)\sum_{q=u,d} c_q(\bar{q}\gamma_\mu q), \qquad O_2 = \frac{ec_2}{\Lambda^2}\partial_\mu F^{\mu\nu}(\Phi^*\overleftrightarrow{\partial_\mu}\Phi), \tag{2.1}$$

which for $c_q \approx c_2 \approx 1$, as expected from NDA, give comparable effects. Taking O_2 for concreteness, the non-relativistic cross section of Φ on a nucleus of charge Z and mass $m_N \ll m_\Phi$ is, up to form factor effects,

$$\sigma_2 = c_2^2 \frac{e^4 Z^2 m_N^2}{\pi\Lambda^4}. \tag{2.2}$$

For Germanium target this corresponds to the per-nucleon cross section

$$\frac{\sigma_2}{A^4} \approx c_2^2 \, 2 \cdot 10^{-7}\text{pb}\left(\frac{\text{TeV}}{\Lambda}\right)^4, \tag{2.3}$$

to be compared with the CDMS limit on the coherent spin-independent cross section [5]

$$\frac{\sigma_{\text{SI}}}{A^4}|_{\exp} \lesssim 2 \cdot 10^{-7}\text{pb}\left(\frac{m_{DM}}{\text{TeV}}\right) \qquad (m_{DM} \gg m_{\text{Ge}}), \tag{2.4}$$

i.e.

$$c_2 < \left(\frac{\Lambda}{\text{TeV}}\right)^2\left(\frac{m_\Phi}{\text{TeV}}\right)^{1/2}. \tag{2.5}$$

For $c_2 \approx 1$, and $\Lambda \approx m_\Phi \approx 4\pi v \approx 3$ TeV, where $v \approx 250$ GeV is the electroweak VEV, the expected cross section (2.3) is about two orders of magnitude below the CDMS limit.

If instead Φ is a Dirac fermion, assuming parity invariance (up to anomalies) of the EWSB forces, the dominant operator is a magnetic moment interaction

$$O_M = \frac{iec_M}{2\Lambda}(\bar{\Phi}\sigma_{\mu\nu}\Phi)F^{\mu\nu}. \tag{2.6}$$

In Germanium, O_M gives rise to the dominant spin-independent cross section due to scattering on the current produced by the nuclear charge:

$$\frac{d\sigma_M}{dE} \approx c_M^2 \frac{e^4 Z^2}{4\pi\Lambda^2 E}(1 + \mathcal{O}(E/E_{\max})), \tag{2.7}$$

where E is the kinetic energy of the recoiling nucleous, ranging from the experimental threshold ~ 10 keV to $E_{\max} = 2v^2 m_N^2 = \mathcal{O}(100$ keV$)$. The spin-dependent cross section is subleading due to small nuclear spin of Germanium and because of $E_{\max}/E$ enhancement present in (2.7) [4]. A suitable comparison of this cross section with the null CDMS result gives in this case

$$c_M < 10^{-1} \left(\frac{\Lambda}{\text{TeV}}\right) \left(\frac{m_\Phi}{\text{TeV}}\right)^{1/2}, \tag{2.8}$$

against the NDA estimate $c_M \approx 1$. Given the uncertainties of these estimates and of the value of the scale Λ itself, in no way this bound can be interpreted as ruling out a composite fermionic DM particle. Quite on the contrary, the message we draw is that a signal in direct DM searches could be around the corner. Yet we find it preferable, at least for reference, to stick in the following to the scalar case.

3 The DM-nucleus interaction mediated by a vector iso-singlet V

Suppose that a positive signal were indeed found in direct DM searches at the level indicated above, in fact not far from the present sensitivity. How would we know that the candidate DM particle is a composite Φ-like particle? As already mentioned, LHC should come into play here. However the detection at LHC of an electroweak-neutral particle of TeV mass that can only be pair produced may not be an easy task. For this reason, we turn the question into a different but related one. What could mediate the operators in Eq. (2.1) responsible in the first place

for the direct DM signal? We argue that the most likely candidate for this role is a composite vector iso-singlet V, the analog of the ω-meson in QCD, strongly coupled to Φ and mixed with the elementary hypercharge gauge boson B_μ, via the diagram of Fig. 1.
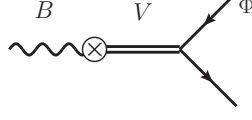

Figure 1: The diagram which generates O_2 via the $V - B$ mixing.

We base our estimates on the following phenomenological Lagrangian

$$\mathcal{L} = \mathcal{L}_V + \mathcal{L}_{V\Phi} \tag{3.1}$$

where

$$\mathcal{L}_{V\Phi} = g_S V_\mu (\Phi^* \overleftrightarrow{\partial_\mu} \Phi), \quad g_S = 4\pi \frac{M_V}{\Lambda}, \tag{3.2}$$

and

$$\mathcal{L}_V = -\frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} M_V^2 V_\mu^2 + \frac{g'}{4\pi} B_{\mu\nu} V_{\mu\nu} - \frac{i}{8\pi} \epsilon^{\mu\nu\rho\sigma} V_\mu \mathrm{tr}(u_\nu u_\rho u_\sigma) + \frac{g}{4\pi} \epsilon^{\mu\nu\rho\sigma} V_\mu \mathrm{tr}(u_\nu \hat{W}_{\rho\sigma}) \tag{3.3}$$

in the standard notation for the electroweak chiral Lagrangian, i.e.

$$u_\mu = iu D_\mu U u^+ \approx i\partial_\mu U + g' B_\mu \frac{\sigma_3}{2} - g W_\mu^a \frac{\sigma_a}{2}, \quad U = u^2 = e^{(i\sigma_a \pi^a / v)}, \tag{3.4}$$

$\hat{W}_{\mu\nu} = W_{\mu\nu}^a \sigma_a / 2$ is the usual field strength for the W boson, and the π-fields are the eaten up Goldstone bosons for EWSB. We assume that the couplings proportional to the epsilon tensor, relevant to the following Section, are induced, analogously to the QCD case, by a chiral anomaly. The strength of the various couplings are all based on NDA estimates, known to work well for QCD [7], and noticing that the only coupling in (3.1) that corrects at one loop level the V-mass M_V is g_S in (3.2).

From the diagram of Fig. 1 it is straightforward to obtain the operator O_2 in eq. (2.1) with

$$c_2 = \frac{2\Lambda}{M_V}, \tag{3.5}$$

or, from (2.5),

$$M_V > 2\,\mathrm{TeV} \left(\frac{\mathrm{TeV}}{\Lambda}\right) \left(\frac{\mathrm{TeV}}{m_\Phi}\right)^{1/2}, \tag{3.6}$$

which could easily allow, taking $\Lambda \approx m_\Phi \approx 4\pi v \approx 3$ TeV, a V-mass as low as 700 GeV. The iso-singlet nature of V makes its exchange innocuous in the ElectroWeak Precision Tests, giving a contribution to the Y-parameter [6] well below the 10^{-4} level.

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4 LHC phenomenology of V

The Lagrangian (3.3) allows to calculate the decay widths of V. The relevant widths are:

- From the last term in (3.3), the dominant decay into two standard vector bosons[3]

$$\Gamma_{\text{tot}} \approx \Gamma \left(V \to W^+ W^-, ZZ, Z\gamma \right) = \frac{g^2}{8\pi} \frac{M_V^3}{(4\pi v)^2} \,, \tag{4.1}$$

$$\text{BR} \left(V \to W^+ W^- \right) \approx \frac{2}{3}, \qquad \text{BR} \left(V \to ZZ \right) \approx \frac{\cos^2 \theta_W}{3}, \qquad \text{BR} \left(V \to Z\gamma \right) \approx \frac{\sin^2 \theta_W}{3} \,. \tag{4.2}$$

- From the last but one term in (3.3), the 3-body decay

$$\Gamma \left(V \to W_L^+ W_L^- Z_L \right) = \frac{\pi}{40} \frac{M_V^7}{(4\pi v)^6} \,. \tag{4.3}$$

- From the mixing of V with the B boson, the decay into a pair of standard fermions, e.g.

$$\Gamma \left(V \to e^+ e^- \right) = \frac{5}{24\pi} \left(\frac{g'^2}{4\pi} \right)^2 M_V \,. \tag{4.4}$$

The total width and the subdominant branching ratios are shown in Fig. 2 for M_V around 1 TeV. A few features are especially apparent from these figure: the smallness of the Γ/M ratio and the strong dominance of the decays into two bosons (among which the $Z\gamma$ channel) over all the other decay modes, in particular the three body $W^+ W^- Z$. Especially this last feature is at variance with what one might have expected from the analogy with the ω in QCD. The main reason for this can be traced back to the close degeneracy of the ω with the ρ, as dictated by $SU(3)$, making the decay $\omega \to 3\pi$ dominated by the intermediate $\pi\rho$ state.

The vector V can be produced at the LHC by the Drell-Yan (DY) process or by Vector Boson Fusion (VBF), as again described by the Lagrangian (3.3). The corresponding production rates are shown in Fig. 3. From the branching ratios above, the $Z\gamma$ channel appears most promising. In Fig. 4 we show the number of events expected when the Z decays into $l^+ l^-, l = e, \mu$ or into $\nu\bar{\nu}$ respectively at $\sqrt{s} = 14$ TeV. The binnings of the events, crucial for discovery, are based on current estimates of the expected resolutions in an advanced phase of LHC operation[4] The background

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[3]This formula corrects a factor 9 error in the RHS of Eq. (4.7) of [7].

[4]We are assuming a 1% energy resolution of the invariant mass of the $l^+ l^- \gamma$ system (comparable to the peak resolution in the $H \to \gamma\gamma$ studies) and a 0.5% resolution of the photon p_T. The binnings correspond to 2σ bins.
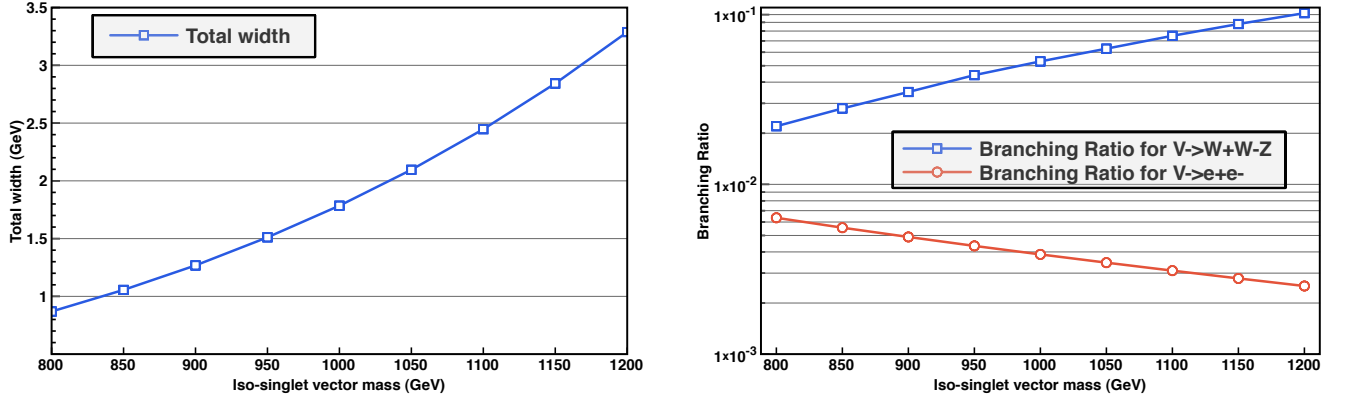
Figure 2: Left panel: the total width of the iso-singlet vector boson V as a function of its mass around 1 TeV. Right panel: the subdominant branching ratios $BR(V \to e^+e^-)$ and $BR(V \to W^+W^-Z)$.
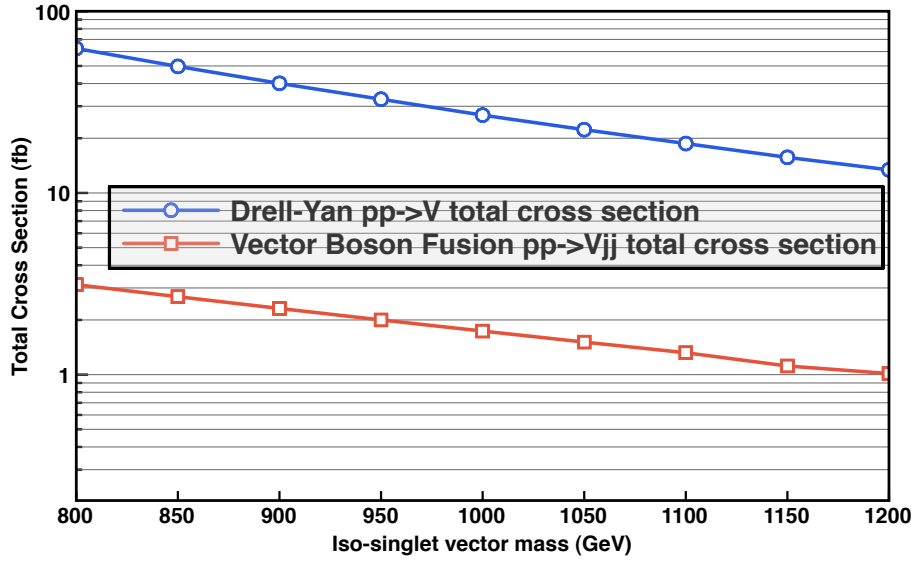

Figure 3: Total cross sections for the Vector Boson Fusion and the Drell-Yan iso-singlet vector boson production at the LHC as funcions of its mass for $\sqrt{s} = 14$ TeV.

shown corresponds to the $Z\gamma$ production in the Standard Model. On the basis of these figures, we conclude that the vector V in the TeV mass range could be discovered at LHC with about 100 fb^{-1} of integrated luminosity.[5]
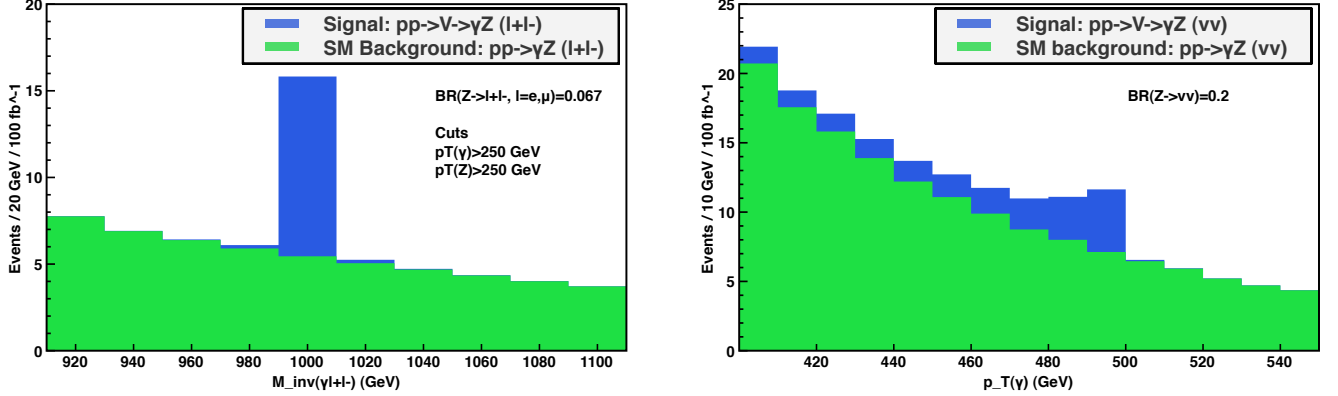

Figure 4: Left panel: the number of γl^+l^- events as a function of the total invariant mass. The imposed $p_T > 250$ GeV cut on the photon and the reconstructed Z boson enhances the S/B ratio. A $\sim 5\sigma$ excess from the SM prediction can be seen. Right panel: the number of $\gamma + \not{E}_T$ events as a function of the photon transverse momentum. This decay mode will give additional information although not a discovery ($S/\sqrt{B} \sim 2$). Both plots are for 100 fb^{-1} of data at $\sqrt{s} = 14$ TeV. The chosen binnings correspond to twice the expected experimental resolution.

5 Summary and conclusions

The strong-coupling scenarios of EWSB deserve attention in spite of generic difficulties in satisfying the ElectroWeak Precision Tests. Due to the lack of calculability, one is forced to use a phenomenological Lagrangian description of the low-lying resonances with coefficients of various operators estimated from NDA. This philosophy has been often applied in the studies of the isospin-1 resonances ('techni-ρ') [9]. In this paper, we used it to study another interesting generic corner of the strong sector, consisting of an iso-singlet vector V ('techni-ω') coupled to the lightest particle Φ carrying nonvanishing conserved charge ('techni-baryon number'). The Φ is a candidate DM particle, assumed electroweak-neutral to evade direct detection constraints[6].

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[5]See [8] for a recent DØ search of narrow vector resonances decaying into $Z\gamma$ based on 1 fb^{-1} of Tevatron data. The resulting limit on $\sigma \times$B.R. is $\sim 0.2 - 0.4$ pb (95% C.L.) for $M_V = 700 - 900$ GeV, two orders of magnitude above the values predicted by our model.

[6]For the alternative possibility of a neutral iso-triplet component, see [10].

We have shown that the phenomenology of this sector allows for an interesting interplay between the ongoing direct DM searches and the LHC. Apart from NDA, our main assumption is that the operators describing interactions of Φ with the SM particles, Eq. (2.1), are generated via the cubic $\Phi\Phi V$ coupling in the strong sector, and the mixing between V and the elementary hypercharge gauge field B, Fig. 1. This is the Vector Meson Dominance hypothesis, which is known to work well in QCD not only for the pion [7] but also for the nucleons [11]. Two conclusions transpire from our analysis. First, the expected signal in direct detection experiments, estimated already in [4], is not far from the present experimental bounds. Second, the isosinglet vector V, in its typical mass range and with couplings as in (3.3), appears within reach of the LHC with $\mathcal{O}(100\text{fb}^{-1})$ integrated luminosity[7]. Its strong sector nature will be easily identifiable due to a characteristic $Z\gamma$ decay mode. The joint observation of nuclear recoil events in direct detection experiments and of a vectorial resonance decaying into $Z\gamma$ at the LHC will then point to a composite DM-particle.

Acknowledgements

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[7] For an old study of the techni-ω discovery potentials at the SSC see [12]. That study correctly identifies the crucial $Z\gamma$ decay mode. Our approach to estimating the production cross section is more direct, in our opinion.

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